

Effect of Injector Geometry on Atomization of a Liquid-Liquid Double Swirl Coaxial Injector using Non-Invasive Laser, Optical and X-ray Techniques

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The spray characteristics of a Liquid-Liquid Double Swirl Coaxial Injector were studied using non-invasive Optical, Laser, and X-ray diagnostics. A parametric study of injector exit geometry demonstrated that spray breakup time, breakup type and sheet stability could be controlled with exit geometry. Phase Doppler Particle Analysis characterized droplet statistics and non-dimensional droplet parameters over a range of inlet conditions and for various fluids allowing for a study on the role of specific fluid properties in atomization. Further, x-ray radiographs allowed for investigations of sheet thickness and breakup length to be quantified for different recess exits and inlet pressures. Finally Computed Tomography scans revealed that the spray cone was distinctively non-uniform and comprised of several pockets of increased mass flux.

I. Introduction

Uniform mixing and fast atomization of liquid propellants are critical for stable and efficient operation of rocket engines. Several types of rocket injectors have been successfully designed and tested in liquid rocket engines including like- or unlike-doublet, triplet, and pentad style impinging jets, as well as pintle and coaxial style injectors. The focus of this study is on liquid-liquid double swirl coaxial injectors, which are advantageous for their scalability and consistent spray and atomization dynamics over a range of operating conditions [1] [2].

Several studies have been performed investigating double swirl coaxial injectors. Sivakumar and Raghunandan performed detailed experimental studies on the mutual interaction between thin coaxial conical sheets and found that several flow breakup regimes exist for the merged fluid sheet and that the flow regime is largely a function of Weber number [3]. Additionally, they found that at certain regimes, hysteresis can occur and cause large variations in spray characteristics such as drop size distribution and disintegration behavior [4]. Other investigations in liquid-liquid coaxial injectors have found that geometrical parameters, particularly recess length, as well as the velocity and the momentum ratio between the liquid sheets can significantly affect the propellant atomization [2] [5]. These studies follow extensive investigations into gas-liquid coaxial injectors which have also pointed to recess length, velocity ratio, and momentum ratio as drivers in atomization and combustion efficiency in bi-propellant rocket injectors [6] [7] [8] [9] [10] [11].

The primary objective of this work is to investigate atomization and spray characteristics of a liquid-liquid double swirl coaxial injector over a range of inlet conditions, exit geometry, and with different fluids in a rocket injector designed for parametric study. Of particular interest is an understanding of spray cone angle and breakup process over a range of inlet pressures as well as a comparison of breakup length for different exit geometries. Finally, an understanding of spray cone uniformity is sought for comparison with future computational models and insight into predicted combustion stability.

II. Injector Design

A 70 lbf (312 N) thruster was designed as a subscale test article for the NASA Project Morpheus vehicle main engine. The engine was designed to operate on pressure fed subcritical liquid oxygen and liquid methane over a stable throttle range of 4:1, with a goal to exhibit stable throttling to 8:1. To enable rapid variation of test conditions,

a modular design was created that allowed for several parameters to be changed easily. Specifically, 6 different recess geometries were designed to allow for a parametric study on exit geometry. Additionally, the injector was designed to easily change the direction of rotation of the inner spray cone to the outer spray cone for a study on the significance of momentum transfer on combustion stability and efficiency.

Several specific geometrical features were incorporated into the uni-element injector. The exit geometries were designed not only with specific exit diameters, but with an axial exit section adjacent to an angled trumpet discharge section. This feature differs from previous exit recess comparisons with liquid-liquid coaxial injectors and was implemented based on work by Xue et al., who found that flow characteristics such as spray cone angle and film thickness could be controlled by the discharge length and trumpet angle without affecting element pressure drop or discharge coefficient in simplex atomizers [12]. Further, an axially symmetric cylindrical recess near the tangential inlets of the LOX swirl chamber was included following work by Kim et al., who demonstrated that the variance in liquid sheet thickness exiting the nozzle could be reduced by anchoring the centrally rotating air core with a cylindrical recess [5]. Combined, the present design incorporates features from several investigations to potentially improve performance beyond previous work.

III. Experimental Setup

Non-invasive techniques are useful for understanding highly sensitive flow phenomena in atomizing sprays. Even measurement techniques such as force and pressure transducers can alter the “true” flow characteristics irreversibly, potentially leading to inaccurate data and conclusions. In order to avoid such effects, non-invasive optical and X-ray imaging techniques were utilized in the current work.

Due to cost considerations, a series of non-reacting injector tests were utilized for the parametric study. Several experiments were performed to characterize the effects of geometry on atomization and to study how different fluid properties affect atomization for a fixed geometry. Because of the wide range of intended throttle points, flow rates through the injector were varied from approximately 0.02 to 0.1 kg/second, and experiments were performed with water, methanol, acetone and JP-8.

To qualitatively measure spray breakup characteristics, high speed images of the spray were collected at speeds that were sufficient to capture the high-speed flow phenomena occurring in the atomizing spray. This data was collected using a Photron FASTCAM SA5 camera with an $f/1.2$ lens. The FASTCAM SA5 camera utilizes a 12-bit ADC and a CMOS sensor with a 20 μm pixel size. The camera uses an electronic shutter with a range between 16.7 ms to 1 μs independent of the frame rate. For each flow scenario, at least 250 images were collected at both 12 kHz and 20 kHz. Images recorded at 12 kHz were collected with 896x816 resolution while images recorded at 20 kHz were collected with 706 x 632 resolution. All images were saved as Tiff files for transferability across different software platforms. To ensure accurate data, adequate time was given to ensure thermal equilibrium was reached in the camera before data was collected. Additionally, 10 dark current images were collected with the lens covered for each flow case to allow subtraction of baseline electronic noise from each image.

To collect simultaneous droplet size and velocity measurements, a Phase Doppler Particle Analyzer (PDPA) was used. The Phase Doppler Particle Analyzer consisted of a Spectra-Physics Sabilite 2017, 6.0 Watt Argon laser, a Fiberlight™ Multicolor Beam Separator, a TSI model PDM1000 Photodetector Module, a TSI Model FSA 3500/4000 Signal Processor, and a TSI PDPA Receiver and Transmitting Probe. The data was routed via firewire to a desktop computer and operated using the TSI FlowSizer™ software. The Spectra-Physics Sabilite 2017 laser was capable of emitting 1.5 Watts of power at 488.0 nm and 2.0 Watts of power at 514.5 nm. The emitted beam diameter was 1.4 mm with a 0.5 mrad divergence at 514.5 nm and with an optical noise less than 0.5% rms. The emitted laser beam is then sent into a Fiberlight™ Multicolor Beam Separator and light is then emitted through a transceiver probe. The received signal is then sent to the Model PDM 1000 photodetector module where the optical signal is converted to an electronic signal and then recorded by the Model FSA 3500/4000 signal processor. To maintain high spatial accuracy, a two-dimensional adjustable steel truss system was built as the platform for stably mounting the injector. In addition to damping out vibrations, adjustable rails allowed for accurate and repeatable vertical

placement in the spray and prevented movement of the spray into and out of the convergence volume of the 4 incident beams. The placement of the point measurements along the rail was achieved using a caliper and verified using digital photographs taken with a Canon DSLR camera. 360 data runs were recorded as part of the PDPA analysis. For each run, a minimum of 2000 valid sample points were collected. The statistics of these samples was collected using the TSI FlowSizer software and exported back into Matlab. To understand the evolution of the spray, high spatial accuracy was maintained throughout the analysis.

X-ray computed tomography scans were taken at the Iowa State University X-ray Flow Visualization Facility. The X-ray source utilizes twin LORAD LPX200 portable sealed-tube sources positioned at right angles on a rotating ring. The supply current and voltage can be adjusted from 0.1 to 10 mA and 10 to 200 kV respectively (Meyer, et al., 2008). Imaging is performed using a $44\text{ cm}^2 \times 44\text{ cm}^2$ cesium-iodide scintillator screen allowing for visible light to be imaged using an Apogee Alta U9 CCD camera capable of variable exposure times at resolutions up to 3072×2048 . Digitally reconstructed tomography is possible by taking a series of 360 radiographs at 1 degree of separation. These images can then be reconstructed using a 64 node LINUX cluster in the Iowa State Center for Non-destructive Evaluation [13].

Due to the low X-ray absorption cross-section of water, the water sprays were mixed with 30% by mass potassium iodide (KI) to increase image contrast. To ensure that the attenuation coefficient is linear with the concentration of KI or equivalently the liquid path length a cuvette study was performed for KI concentrations ranging from 10-50% with a 5 mm cuvette. A linear increase in the attenuation coefficient with KI concentration indicates that the effects of beam hardening are minimal. Beam hardening takes place when lower energy (softer) X-rays are completely absorbed and any additional KI or liquid in the remaining path freely transmits the remaining higher energy (harder) X-rays without any further absorption. In this case, the spectrum of the X-rays becomes harder as they pass through the liquid. This is a potential problem with the use of polychromatic tube-source X-rays and is not a problem when using narrowed synchrotron X-ray radiation. By ensuring that beam hardening (non-linear) behavior is not present from 10-50% KI in the 5 mm cuvette, it ensures that beam hardening will not lead to errors in relating X-ray absorption to the liquid mass, or equivalently liquid path length. Previous works have verified that the attenuation coefficient is linear with KI concentrations up to 15% for 1 cm path lengths [14]. Hence, for one-half the liquid path length of 5 mm, it is expected that beam hardening can be avoided with KI mass fractions up to 30%.

IV. Results

High Speed Imaging

A series of high speed images of water atomization were collected at different injection pressures and over 5 different geometric parameters. For each injection pressure, 250 images were taken at both 12 kHz and 20 kHz. 12 kHz images were recorded at 896×816 resolution and images taken at 20 kHz were recorded at 704×632 resolution. A comparison for different liquids was also conducted, including acetone, methanol, and JP-8. The images were then post processed for dark current removal and digital filtering.

Investigation of Recess Designs

An investigation into internal mixing was performed using high speed imaging. To perform this investigation, a series of photographs was taken of the spray at the nozzle exit for the 5 different recess designs. The recess design is shown schematically below. Each recess design contains 4 adjustable parameters: cylindrical inner diameter D_i , cylindrical length L_c , trumpet length L_t and trumpet or exit half angle θ . For each of the 5 different geometries studied here, the injection pressure was varied from 69 kPa (10psi) – 620 kPa (90 psi) in ~69 kPa intervals. Images were taken at two frame rates with the maximum resolution available.

In order to quantify droplet size and velocity statistics, PDPA was performed on the injector while varying fluid properties and injection pressure. PDPA data was collected in 3 horizontal slices across the atomizing liquid

sheet. Based on high-speed images, it was inferred that horizontal slices closer than 25 mm to the injector would not reveal accurate flow structure because of a large percentage of the flow would still be entrapped in stable liquid sheet structures that had not atomized, particularly at low pressures. It was then inferred from preliminary data collections runs that slice at 50 mm and 75 mm from the nozzle exit would effectively quantify differences in atomization evolution. It was anticipated that finely atomized sprays would have higher droplet counts and wider distributions of diameters and velocities, while sprays still atomizing would produce larger droplets still in the process of breaking up.

Previous studies in injector dynamics have shown that non-dimensional parameters such as droplet Reynolds and droplet Weber number are keen indicators of atomization regime and can be keen indicators of future hot-fire performance. To explore this, plots were created of Weber number and Reynolds number as injector inlet pressure was increased where droplet weber number and droplet are given as:

$$We_{droplet} = \frac{\rho u^2 d_{32}}{\sigma} \quad Re_{droplet} = \frac{\rho u d_{32}}{\mu}$$

Droplet diameter measurements provide insight into the droplet formation of the atomizing spray. Several statistical techniques were used to analyze droplet data of the injector over a range of fluids and pressures. Droplet size histograms were used to investigate droplet diameter distributions at points within the spray. By studying the distributions, insight into the variations of droplets sizes at points can be studied providing insight into physical mechanisms driving breakup. Additionally, sauter mean diameter values provide insightful point averaged droplet statistics. The SMD point values allow for baseline comparisons between different fluids and different pressures.

X- Imaging

Two techniques that have proven the ability to measure mass distributions is X-ray radiography and 3-D X-ray computed tomography (CT). To increase visual contrast in the study, a potassium iodide (KI) contrast enhancing agent was mixed with the fluid prior to each experiment. A preliminary study was done to determine an effective amount of KI by taking radiographs over a range of KI % and , it was determined that a 30% solution would provide sufficient absorption. In order to verify that the absorption coefficient of KI is still linear with KI concentration in the range of path lengths between 2.5-5mm, a cuvette study was performed. The study was performed by mixing known concentrations of KI in cuvettes of known path length. The intensity of signal through the fluid medium can then be compared to the intensity of background signal allowing for an absorption coefficient to be calculated in accordance with Beers law.

X-ray Radiography

X ray radiographs were taken to investigate variations in sheet thickness among different recess design segments and at different injection pressures. Experimental values for sheet thickness were computed by comparing signal intensity at axial locations in the spray to signal values immediately adjacent to the spray. This ratio of signal was then correlated into a path length equal to both fluid sheets by using the previously found absorption coefficient. Example radiographs and calculated thickness at a fixed inlet pressure are shown below.

X-ray Computed Tomography

Next, a series of 3-D CT reconstructions were created and studied which revealed several quantifiable characteristics. Firstly, results indicate that fluid density in the liquid sheet region of the spray is not axi-symmetric as indicated by 3 regions of increased density in the midline of the spray.

An explanation of this phenomenon is not immediately available. However, several hypotheses have been proposed. Previous work on acoustic stability [4] has shown that wave propagation from initial sheet formation regions internal to the geometry may be creating an acoustic resonance leading to flow bias. However, because CT scans used in the production of this reconstruction were taken using 1 second exposures, any acoustic phenomena would need to interact on time scales is near or in excess of the 1 second integration time.

Another hypothesis proposed is that small differences in geometrical factors relevant to the injection, such as injection diameters or internal length scales of the fluid may have resulted in flow bias through one, or several injection orifices. While all geometrical quantities of interest were manufactured within narrow tolerances, and all measured to within 5 hundredths' of an inch, discrepancies within these ranges may still result in this observed flow phenomena.

Finally, it is worth noting that these discrepancies seem to have an effect in the distribution of mass along the axis of travel. It is seen from the iso-metric view of the cone, that the mass fraction has 3 local maximums that stem from regions of increased density at the top. This indicates that not only does the flow discrepancy affect regions of solid or continuous liquid sheets, but that the bias is maintained in regions of aerodynamic breakup

It should be noted that the density bias could create acoustic instability if present at injection conditions used at operation. Because of this implication, further investigation is desired to help better understand the nature of this flow bias

V. Summary and Conclusions

The spray characteristics of a Liquid-Liquid Double Swirl Coaxial Injector were studied using non-invasive Optical, Laser, and X-ray diagnostics. A parametric study of injector exit geometry demonstrated the role that exit diameter, trumpet diameter and trumpet angle play in controlling spray breakup time, breakup type and sheet stability. Phase Doppler Particle Analysis was then used to characterize droplet statistics and non-dimensional droplet parameters over a range of inlet conditions and for various fluids allowing for a study on the role of specific flow properties in atomization. Further, x-ray radiographs allowed for investigations of sheet thickness and breakup length to be quantified for different recess exits and inlet pressures. Finally Computed Tomography scans allowed for insights into mass distributions to be studied. It was revealed that the spray cone was distinctively non-uniform and comprised of several pockets of increased mass flux.

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